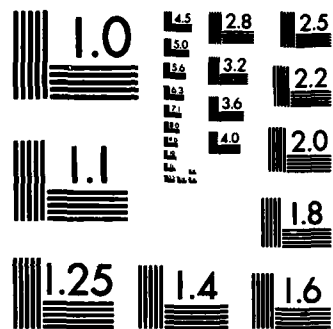MICROCOPY RESOLUTION TEST CHART

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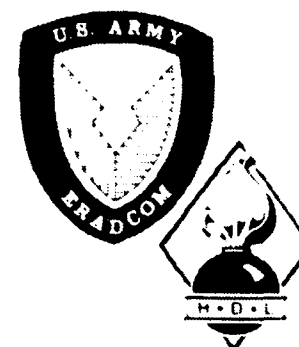October 1982

High-Power Microwave Source Requirements for a Relativistic Electron Accelerator

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An estimate is made of the high-power microwave source intensity required to drive a relativistic electron accelerator of the type proposed some time ago by A. A. Kolomenskii and A. N. Lebedev. In this acceleration method, an external static magnetic guide field is chosen such that the particles are steered in such a way that the electric field of the microwave source performs positive work on them on the average. This calculation is intended only to provide a point of reference for this and other

20. ABSTRACT (Cont'd)

types of high-power microwave driven electron accelerators. Al-
though the required intensity for the above approach exceeds
present capabilities, intensive research in the development of new
high-power microwave sources may change this.

CONTENTS

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1. INTRODUCTION

Some time ago, Kolomenskii and Lebedev proposed a simple method of accelerating charged particles to high energy with an electromagnetic wave together with an orbit-synchronizing magnetic field.[1]* The spatial dependence of the external static magnetic guide field is chosen to effectively steer the particles in such a way that the electric field of the wave performs positive work, on the average, on the particles. Already at the time that this method was proposed, the appreciable increases attained in the power of microwave sources that might be used for such an accelerator were stressed.

More recently, several other methods have been proposed for accelerating electrons by using the electromagnetic energy of a radiation field together with a periodic static magnetic guide field.[2-5] Other approaches are also of current interest, involving the interaction between an intense electromagnetic wave packet and the electrons of an underdense plasma.[5-9] Also related is the method of radiative collective acceleration proposed long ago by Veksler.[10]

Although most of these schemes have emphasized conventional laser sources, Sprangle has recently considered a free electron laser source operating at submillimeter frequencies.[4] Recent advances in the development of high-power microwave sources[11-31] make it not unreasonable that sources of sufficient intensity to drive an electron accelerator can be developed.

Within the limited means of the present work, a simple estimate is here made of the required microwave power requirements to drive a relativistic electron accelerator of the type originally proposed by Kolomenskii and Lebedev.[1] The analysis presented here follows theirs closely with added mathematical detail and graphical presentation of the results.

In section 2, an estimate is made of the required high-power microwave source intensity for such an electron accelerator in the relativistic regime, in terms of the final electron energy and the accelerator length. These calculations assume a set of constraints on the microwave frequency, the electron energy, and the perturbed electron velocity that facilitate mathematically convenient approximations. In section 3, the results and the conclusions are summarized. The limitations of the present analysis are to be emphasized. It is likely that more detailed examination of the problem including collective effects and less limited mathematical constraints will generate an even more optimistic picture.

See Literature Cited section for all references.

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2. ESTIMATE OF MICROWAVE SOURCE REQUIREMENTS

In the accelerator approach proposed by Kolomenskii and Lebedev,[1] an electron beam is considered to traverse the accelerator region axially along the positive z-axis of a right-handed rectangular cartesian coordinate system. A microwave accelerating wave linearly polarized in the y-direction also moves in the positive z-direction. The electromagnetic wave is of the form

$$\vec{B} = -\hat{x}E_m \sin(\omega t - kz) \quad , \tag{1}$$

$$\vec{E} = \hat{y}E_m \sin(\omega t - kz) \quad . \tag{2}$$

A magnetic guide field is assumed of the form

$$\vec{B}_g = \hat{x}B_o(y,z) \tag{3}$$

such that the perturbed particle trajectories are guided in such a way that the microwaves perform, on the average, positive work on the particles, thereby accelerating them. Collective effects are ignored.

The rate of work, $\dot{\varepsilon}$, on a beam electron is given by

$$\dot{\varepsilon} = ec\vec{\beta} \cdot \vec{E} = ec\beta_y |\vec{E}| \quad , \tag{4}$$

where $-e$, $\vec{\beta}$, and ε are the charge, the velocity (in units of the speed of light), and the energy of the electron. In order that $\dot{\varepsilon}$ be on the average positive, Kolomenskii and Lebedev assumed a magnetic guide field such that the component of particle velocity in the y-direction is in phase with the electric field of the wave, namely,

$$\beta_x = 0 \quad , \tag{5}$$

$$\beta_y = \beta_\perp(\gamma) \sin(\omega t - kz) \quad . \tag{6}$$

Here $\beta_\perp(\gamma)$ is some positive and slowly varying function of z, or equivalently a function of the γ of the beam, where

$$\gamma = \left(1 - \beta^2\right)^{-1/2} \quad . \tag{7}$$

The electrons are thus assumed to be confined to the y-z plane. To see that this results in positive work on the average, one first substitutes equations (2) and (6) into equation (4). Thus

$$\dot{\varepsilon} = ecE_m\beta_\perp(\gamma) \sin^2(\omega t - kz) \tag{8}$$

and taking the time average, then

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$$\langle \dot{\varepsilon} \rangle = \frac{1}{2} ecE_m\beta_\perp(\gamma) > 0 \quad , \tag{9}$$

which is positive since all quantities e, c, E_m, and $\beta_\perp$ are positive numbers.

It is useful to define the phase, ϕ, appearing in equations (1), (2), and (6), namely,

$$\phi \equiv \omega t - kz \quad . \tag{10}$$

Substituting

$$z = \int \dot{z} \, dt = \int \beta_z c \, dt \tag{11}$$

into equation (10), then

$$\phi = \omega t - kc \int \beta_z \, dt \quad . \tag{12}$$

Equivalently, equation (12) can be rewritten as

$$\phi = \int \left(\omega - kc\beta_z \right) dt \quad . \tag{13}$$

Kolomenskii and Lebedev assumed that the transverse velocity of the beam electrons is much less than the longitudinal; hence in equation (7),

$$\beta_\perp \ll \beta_z \quad . \tag{14}$$

It then follows by using equations (5) and (14) that

$$\beta = \left(\beta_x^2 + \beta_y^2 + \beta_z^2 \right)^{1/2} \approx \beta_z \tag{15}$$

and therefore, for an electron trajectory, one has that

$$dt = \frac{dz}{v_z} = \frac{dz}{\beta_z c} \approx \frac{dz}{\beta c} \quad . \tag{16}$$

Also, for the microwave field, the free space dispersion relation obtains; hence

$$k = \frac{\omega}{c} \quad . \tag{17}$$

Substituting equations (16) and (17) into equation (13), then to first order in $\beta_\perp/\beta_z$,

$$\phi \approx k \int \frac{1 - \beta_z}{\beta} \, dz \quad . \tag{18}$$

Substituting equations (10) and (18) into equation (6), then

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$$\beta_y = \beta_\perp(\gamma) \, \sin\left(k \int \frac{1 - \beta_z}{\beta} \, dz\right) \quad . \tag{19}$$

Next by noting that the energy of an electron of rest mass, m, is given by

$$\varepsilon = \gamma mc^2 \tag{20}$$

and by using equation (10), equation (8) becomes

$$\dot{\gamma} = \frac{eE_m}{mc} \, \beta_\perp \, \sin^2 \phi \quad . \tag{21}$$

Also using equation (10), one has

$$\dot{\gamma} = \frac{d\gamma}{dt} = \frac{d\gamma}{d\phi} \frac{d\phi}{dt} = \frac{d\gamma}{d\phi} \, (\omega - k\dot{z}) \tag{22}$$

or, using equation (17), one has then

$$\dot{\gamma} = \frac{d\gamma}{d\phi} \, kc\left(1 - \beta_z\right) \quad . \tag{23}$$

Substituting equation (23) into equation (21) then gives

$$\frac{d\gamma}{d\phi} = \frac{eE_m}{mc^2 k} \frac{\beta_\perp \, \sin^2 \phi}{1 - \beta_z} \quad . \tag{24}$$

Furthermore, by using equations (5), (7), and (15), then

$$\beta_z = \left(\beta^2 - \beta_y^2\right)^{1/2} = \left(1 - \gamma^{-2} - \beta_y^2\right)^{1/2} \tag{25}$$

or, by using equations (6) and (10), then

$$\beta_z = \left(1 - \gamma^{-2} - \beta_\perp^2 \, \sin^2 \phi\right)^{1/2} \quad . \tag{26}$$

Substituting equation (26) into equation (24) then gives

$$\frac{d\gamma}{d\phi} = \frac{G\beta_\perp \, \sin^2 \phi}{1 - \left(1 - \gamma^{-2} - \beta_\perp^2 \, \sin^2 \phi\right)^{1/2}} \quad , \tag{27}$$

where one defines

$$G = \frac{eE_m}{mc^2 k} \quad . \tag{28}$$

One also has, using equation (10), that

$$\frac{d\phi}{dz} = \frac{d}{dz} \, (\omega t - kz) = k\left(c \, \frac{dt}{dz} - 1\right) = k\left(\frac{1}{\beta_z} - 1\right) \quad . \tag{29}$$

Then by substituting equation (26) into equation (29),

$$\frac{d\phi}{dz} = k\left[\left(1 - \gamma^{-2} - \beta_\perp^2 \, \sin^2 \phi\right)^{-1/2} - 1\right] \tag{30}$$

or, by taking the inverse, then

$$\frac{dz}{d\phi} = k^{-1}\left[\left(1 - \gamma^{-2} - \beta_{\perp}^2 \sin^2 \phi\right)^{-1/2} - 1\right]^{-1} \tag{31}$$

From equations (28) and (30), it follows that

$$\frac{d\phi}{dz} = \frac{1}{G}\left(\frac{eE_m}{mc^2}\right)\left[\left(1 - \gamma^{-2} - \beta_{\perp}^2 \sin^2 \phi\right)^{-1/2} - 1\right] \quad, \tag{32}$$

and the phase is seen to be rapidly varying, provided that

$$G \ll 1 \quad . \tag{33}$$

Since

$$k = \frac{2\pi}{\lambda} \quad , \tag{34}$$

where λ is the wavelength of the microwave field, then using equations (28) and (34), one sees that equation (33) is equivalent to

$$E_m\lambda \ll \frac{2\pi mc^2}{e} \quad , \tag{35}$$

which is the case for a sufficiently short wavelength and not too strong a microwave field.

Also by substituting equation (20) into equation (27), then

$$\frac{d\varepsilon}{d\phi} = G\left[\frac{mc^2\beta_{\perp} \sin^2 \phi}{1 - \left(1 - \gamma^{-2} - \beta_{\perp}^2 \sin^2 \phi\right)^{1/2}}\right] \quad , \tag{36}$$

and it follows that when equations (33) and (35) are satisfied, then the particle energy is a slowly varying function of phase. In other words, the particle energy changes very little over distances of the order of one wavelength. Kolomenskii and Lebedev assumed equation (33) or equivalent equation (35) to be satisfied and therefore were able to find approximate solutions to equations (27) and (30) by averaging over the rapidly varying phase.

Furthermore, they addressed the case of a very relativistic beam, namely, one for which

$$\gamma^{-1} \ll 1 \quad . \tag{37}$$

Also from equation (14), it follows that the transverse velocity is nonrelativistic, namely,

$$\beta_{\perp} \ll 1 \quad . \tag{38}$$

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Next by performing a Taylor series expansion in $\beta_\perp$ and γ^{-1} of the radical in equation (31), then to lowest order

$$\frac{dz}{d\phi} = \frac{2\gamma^2}{k\left(1 + \gamma^2\beta_\perp^2 \sin^2 \phi\right)} \quad . \tag{39}$$

If the wavelength of the microwave source is sufficiently small so that equation (35) is satisfied, then one takes the average over the phase in equation (39), obtaining

$$\langle\frac{dz}{d\phi}\rangle = \frac{2\gamma^2}{k}\left(1 + \gamma^2\beta_\perp^2\right)^{-1/2} \quad . \tag{40}$$

Since the efficiency of the beam increases with increasing $\beta_\perp$ (within limits, of course), one assumes that

$$\gamma^2\beta_\perp^2 \gg 1 \quad , \tag{41}$$

in which case equation (40) becomes approximately

$$\langle\frac{dz}{d\phi}\rangle = \frac{2\gamma}{k\beta_\perp} \quad . \tag{42}$$

Also by expanding equation (27) in γ^{-1} and $\beta_\perp$, then

$$\frac{d\gamma}{d\phi} = \frac{2G\beta_\perp\gamma^2 \sin^2 \phi}{1 + \beta_\perp^2\gamma^2 \sin^2 \phi} \quad . \tag{43}$$

Next by taking the average of equation (43) over the phase, then

$$\langle\frac{d\gamma}{d\phi}\rangle = \frac{2G\beta_\perp\gamma^2}{1 + \beta_\perp^2\gamma^2 + \left(1 + \beta_\perp^2\gamma^2\right)^{1/2}} \quad . \tag{44}$$

Furthermore, using equation (41) in equation (44), one has approximately

$$\langle\frac{d\gamma}{d\phi}\rangle = \frac{2G}{\beta_\perp} \quad . \tag{45}$$

To proceed, one has that

$$\langle\frac{dz}{d\phi}\rangle = \langle\frac{dz}{d\gamma} \frac{d\gamma}{d\phi}\rangle \quad . \tag{46}$$

Kolomenskii and Lebedev assumed that

$$\langle\frac{dz}{d\gamma} \frac{d\gamma}{d\phi}\rangle = \langle\frac{dz}{d\gamma}\rangle\langle\frac{d\gamma}{d\phi}\rangle \tag{47}$$

to the needed order. By substituting equation (47) into equation (46), it then follows that

$$\langle\frac{dz}{d\gamma}\rangle = \langle\frac{dz}{d\phi}\rangle \langle\frac{d\gamma}{d\phi}\rangle^{-1} \quad . \tag{48}$$

Next by substituting equations (42) and (45) into equation (48), then

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$$\langle \frac{dz}{d\gamma} \rangle = \frac{\gamma}{kG} \quad . \tag{49}$$

The length, Z, of the accelerator region is approximately given by

$$Z = \int_{z_i}^{z_f} dz = \int_{\gamma_i}^{\gamma_f} d\gamma \langle \frac{dz}{d\gamma} \rangle \quad , \tag{50}$$

where γ_i and γ_f are the initial and final γ's of the beam. Substituting equation (49) into equation (50) then gives

$$GkZ = \int_{\gamma_i}^{\gamma_f} d\gamma \, \gamma \tag{51}$$

or

$$GkZ = \frac{1}{2}\left(\gamma_f^2 - \gamma_i^2\right) \quad . \tag{52}$$

Next, combining equations (28) and (52), one obtains

$$E_m = \frac{mc^2}{2eZ} \left(\gamma_f^2 - \gamma_i^2\right) \quad . \tag{53}$$

By writing γ_i and γ_f in terms of the initial and final electron total energies, ε_i and ε_f, then

$$\gamma_f = \frac{\varepsilon_f}{mc^2} \tag{54}$$

and

$$\gamma_i = \frac{\varepsilon_i}{mc^2} \quad . \tag{55}$$

By substituting equations (54) and (55) into equation (53), then

$$E_m = \frac{1}{2eZ} \frac{\varepsilon_f^2}{mc^2} \left[1 - \left(\frac{\varepsilon_i}{\varepsilon_f}\right)^2 \right] \quad . \tag{56}$$

Finally by assuming that the final electron energy is much greater than the initial, namely,

$$\varepsilon_f \gg \varepsilon_i \quad , \tag{57}$$

then equation (56) becomes

$$E_m = \frac{1}{2emc^2} \frac{\varepsilon_f^2}{Z} \quad . \tag{58}$$

Equation (58) expresses the amplitude, E_m, of the microwave field in terms of the energy, ε_f, to which the electrons are accelerated and the length, Z, of the accelerator. It is well at this point to summarize the domain of validity of this equation. From equations (14), (41), and (35) follows the following set of conditions in addition to equation (57):

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$$\gamma^{-1} \ll \beta_\perp \ll 1 \quad , \tag{59}$$

$$\lambda \ll 2\pi \frac{mc^2}{eE_m} \quad . \tag{60}$$

Equation (59) is the condition that the beam be relativistic with significant although moderate transverse velocity. Equation (60) is the condition that the high-power microwave source be limited to lower wavelengths. It must be stressed, however, that these constraints on transverse particle velocity and microwave wavelength are ones of mathematical convenience only in that they have merely facilitated the approximations. The regimes of higher $\beta_\perp$ or longer wavelength or both are beyond the means of the present limited effort; however, they are certainly of physical interest. Addressing the mathematical and physical constraints on the magnetic guide field also is beyond the scope of this work.

The intensity of the microwave radiation field is given by the Poynting flux for a plane wave, namely,

$$S = \epsilon_0 \langle E^2 \rangle c \quad . \tag{61}$$

By substituting equation (2) into equation (61) and averaging over phase, then

$$S = \frac{1}{2} \epsilon_0 c E_m^2 \quad . \tag{62}$$

Finally substituting equation (58) into equation (62), one obtains for the required microwave source intensity

$$S = \frac{\epsilon_0}{8e^2 m^2 c^3} \frac{\epsilon_f^4}{z^2} \quad . \tag{63}$$

If the final electron energy is expressed in mega-electron volts and the accelerator length is in meters, then equation (63) may be written as follows for electrons:

$$S = 1.26 \times 10^{-4} \frac{\epsilon_f^4}{z^2} \quad . \tag{64}$$

The intensity, S, is here expressed in gigawatts per square centimeter.

In figures 1 and 2, equation (64) has been used to obtain plots of the required microwave source intensity in gigawatts per square centimeter as a function of the final electron energy in mega-electron volts for various values of the accelerator length in meters. Figure 1 addresses the high energy range from 100 to 500 MeV. For the corresponding range of intensities, the wavelength is restricted to near millimeter or less in accordance with

$$\lambda \ll \frac{\pi m c^2}{e} \left(\frac{2\varepsilon_o c}{S} \right)^{1/2} \quad , \tag{65}$$

which follows from equations (60) and (62). Of course, the intensity requirements of figure 1 ranging from 1 GW/cm^2 to 1 TW/cm^2 in near millimeter exceed present day capabilities. However, it is possible that extensive research efforts will lead to new high-power microwave sources at such levels of intensity. In figure 2 appears a similar plot for the 1- to 100-MeV range of final electron energy. In this plot, the approximations made limit the wavelength to near centimeter or less according to equation (65). The possibility of several consecutive stages of acceleration should be explored.
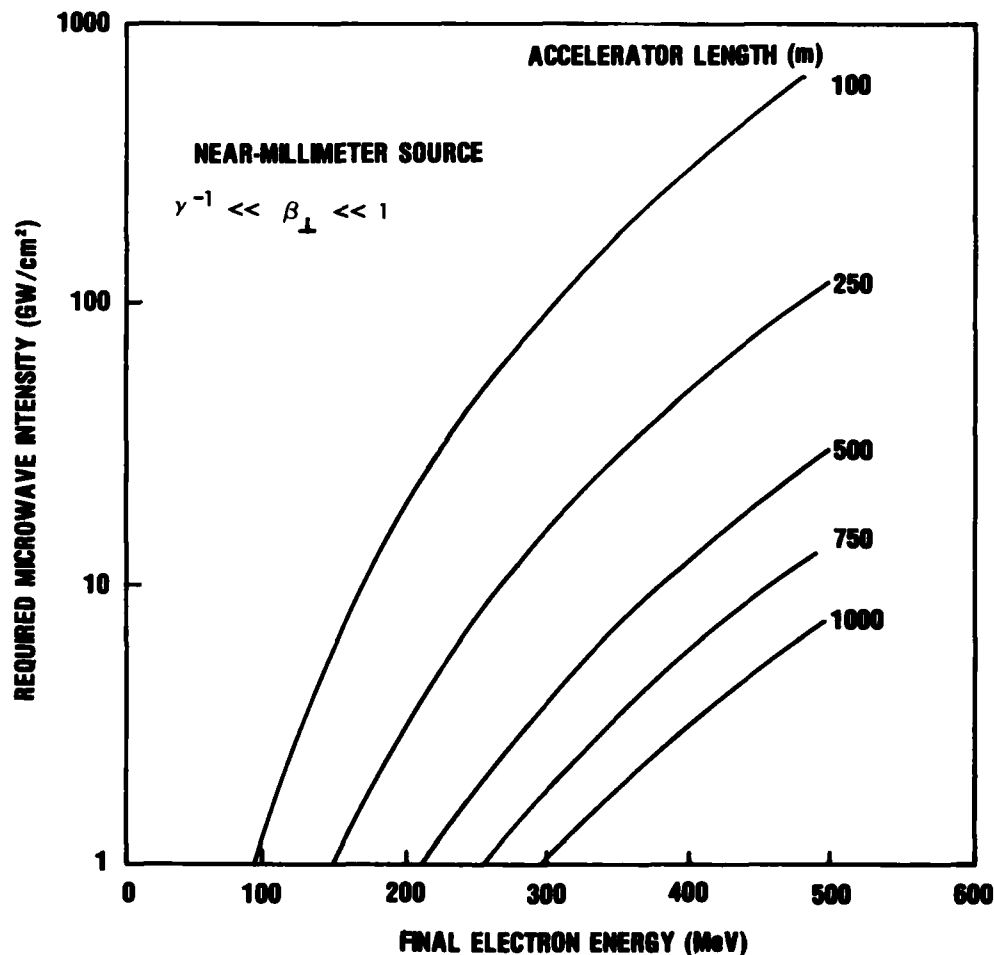

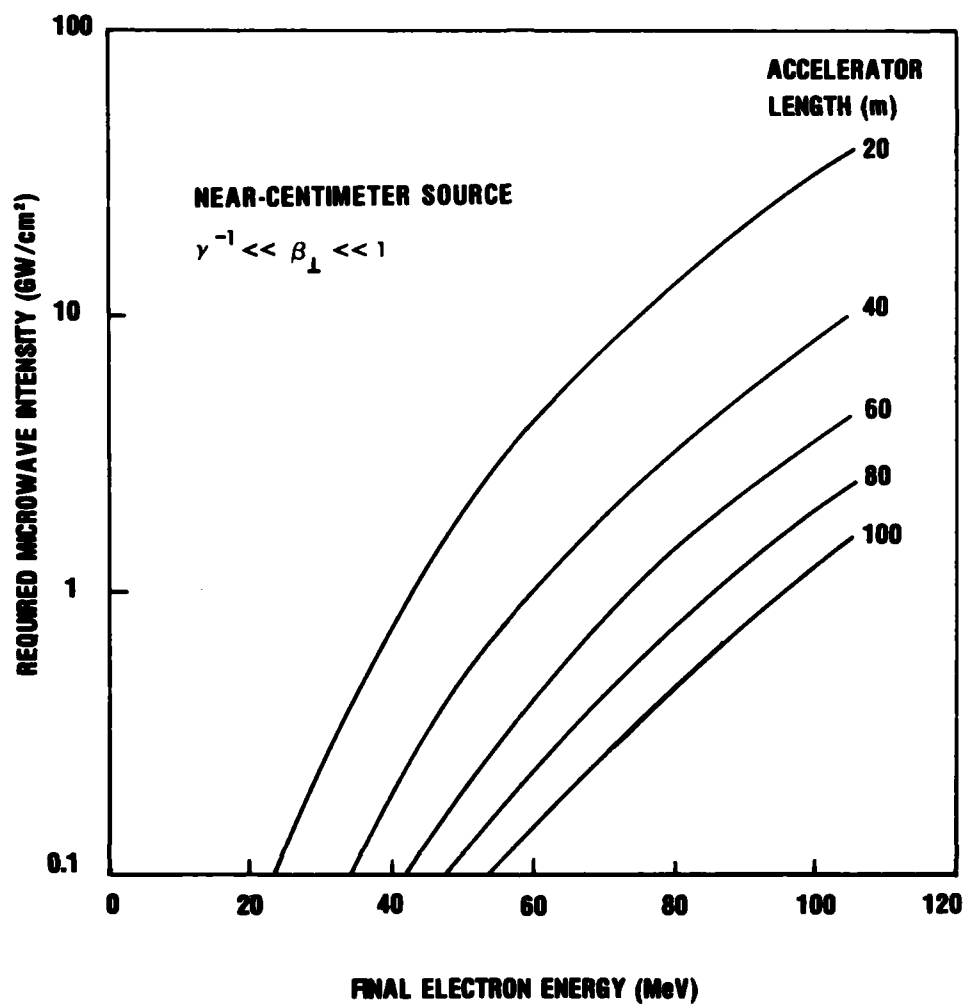Figure 1. Required microwave source intensity as function of final electron energy and accelerator length.

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Figure 2. Required microwave source intensity as function of final
electron energy and accelerator length for lower energies.

3. CONCLUSIONS

Although impressive gigawatt level microwave sources have recently been developed, the microwave intensity required for the acceleration method addressed here in the 100- to 500-MeV range of final electron energies exceeds the capabilities of existing microwave technology. Figure 1 tells us that a near-millimeter microwave source of intensity 30 GW/cm^2 is required to accelerate electrons to 500 MeV for an accelerator length of 500 m. For a 100-m accelerator length, the required intensity would be 800 GW/cm^2.

It is possible that more sophisticated accelerator design together with more elaborate physical theory may improve these estimates to some extent and even make them more favorable. In particular, possible very beneficial collective effects have been totally ignored. Also intensive research in the development of new high-power microwave sources may make the required intensity regime accessible.

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